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DETECTION OF EXTRASOLAR PLANETS BY THE LARGE DEPLOYABLE REFLECTOR

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SUMMARY

Direct detection of the thermal emission from extrasolar planets has been investigated as one of the possible uses of the Large Deployable Reflector (LDR), an orbiting infrared telescope scheduled for launch by NASA in the 1990s. Consideration has been given to two major observational constraints, namely, instrumental sensitivity and angular resolution, in the calculation of detectability of Jupiter-size planetary companions to main sequence stars, white dwarfs, and young stars.

The best wavelength for observation of planetary companions to stars other than the Sun is one at which a planet's thermal emission is strongest; typically this would occur in the far-infrared region, because in this area of the spectrum, the star-planet brightness ratio is much less than it is in the visible portion of the spectrum for a wide range of possible star-planet combinations. It is assumed that the telescope is diffraction-limited so that the resolution of the planet from the central star is accomplished in the wings of the star's Airy pattern. Proxima Centauri, Barnard's Star, Wolf 359, and Epsilon Eridani are just a few of the many nearest main-sequence stars that could be studied with the LDR.

The detectability of a planet improves for warmer planets and less luminous stars; therefore, we have considered the cases of planets around white dwarfs and those young planets which have sufficient internal gravitational energy release so as to cause a significant increase in their temperatures. If white dwarfs are as old as they are usually assumed to be (5-10 billion yr), then only the nearest white dwarf (Sirius B) is within the range of LDR. The Ursa Major cluster and Perseus cluster are within LDR's detection range mainly because of their proximity and young age, respectively.

I. INTRODUCTION

Attempts to discover other planetary systems originate, in part, in man's eternal search for companionship and his desire to find and contact extraterrestrial life forms similar to ours. Regardless of whether communication will ever be established with extraterrestrial civilizations, there are compelling astrophysical reasons for undertaking the search for extrasolar planets: to understand the origin of the solar system and to probe the process of star formation. The current theory of star formation, whereby a large conglomerate of gas and dust gravitationally collapses to form a star, predicts a rather frequent occurrence of multiple star systems and planetary systems. Observational evidence for multiple star systems abound, but there is not a single unambiguous piece of observational evidence for the existence of another planetary system. The detection and study of other planetary systems involves the measurement of very small quantities, such as intensities, Doppler-shifts, and

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parallax shifts, at a level of accuracy that generally far exceeds the capability of currently available technology (ref. 1).

In a recent comprehensive review article on the detection of extrasolar planetary systems, Black (ref. 2) notes that, "although we have knowledge in varying degrees about the nine planets of our solar system, the collective knowledge is not yet sufficient to specify the defining characteristic of a planet in a rigorous, scientifically meaningful manner." Details of how planets form around stars are still a mystery; we will not be able to define exactly what a planet is in terms of fundamental physical characteristics until we understand the comprehensive theory of planet formation. A "planet," however, can be operationally defined as a substellar mass object that is gravitationally bound to a star. There exists an ambiguity as to what constitutes a "substellar mass." Its upper limit is presumably that mass below which gravitational energy is not sufficient to produce temperatures that can trigger and sustain thermonuclear reaction in the interior of the object. This upper limit depends on the composition of the object and is theoretically found to range from 0.001 $M_{\odot}$ to 0.06 $M_{\odot}$ (ref. 2), where $M_{\odot} = 1.99 \times 10^{33}$ g is the solar mass. The mass of Jupiter, for example, is 0.00095 $M_{\odot}$; it may barely have escaped becoming a low-mass star. The lower limit of planetary masses may be defined as the minimum mass for which the object can remain spherical by its own gravitation.

In terms of understanding the fundamental processes of star and planet formation, a "planetary system" should be defined as containing at least two substellar-mass objects in bound, stable, nonhierarchial orbits around a single star (ref. 2). For the purpose of this article, however, we define a planetary system to be any bound system consisting of a star and at least one planet in stable orbit, which eliminates the requirement for nonhierarchial orbital structure. This broader definition will then include a binary or multiple star system which may have planets around any of the stars in the system.

A planet might be detected either directly by observing its radiation, or indirectly by measuring its effects on the central star. The former category (direct detection) includes both thermal and nonthermal radiation from a planet. The thermal component characterizes the planet's effective temperature, which presumably is determined by a balance between energy input (internal heat source and external stellar radiation) and radiative loss from the planet. The bulk of the thermal component generally lies at infrared wavelengths. The nonthermal component involves all the other sources of radiation from the planet. These may include reflected stellar radiation (primarily visual and near-infrared wavelengths) and maser processes in the planet's atmosphere (possibly at radio wavelengths). Indirect detection includes the following three potentially observable effects. First is the planet-induced perturbations in the proper motion of a star against a group of background stars (astrometric detection). Second is the Doppler-shift of the stellar spectrum caused by the planet-induced orbital motion along the line-of-sight (spectroscopic detection). Third is the dimming in the apparent luminosity of a star as a planet moves across the stellar disk, eclipsing part of the star (photometric detection). Detailed analysis of the observables for each of these detection techniques has been given (ref. 2). In this study we shall focus on direct detection of the planet's thermal radiation.

The observations that lead to detection of an extrasolar planet also reveal parameters of the planetary system. The direct detection of the thermal radiation from a planet reveals the temperature of the planet if the intensity can be measured at two or more wavelengths. From the temperature and bolometric luminosity, the size of the planet can be estimated. In a visual direct detection technique, multicolor

observations of the planet could provide information on the nature of the planetary surface that is reflecting the starlight. In both types of direct detection techniques, if observations can yield the orbital period, then the distance between the planet and the star can be determined by using Kepler's third law when given an independent estimate of the mass of the star. Knowledge of the temperature and the distance from the star would help to determine the effective emissivity of the planet, or to infer the existence of atmospheric effects or internal heat sources.

Astrometric and spectroscopic detection could provide data on the planet's mass and its distance from the star, though spectroscopic detection depends, in part, on the inclination angle of the orbital plane relative to an observer's line of sight to the star. The photometric detection of a planet could yield an estimate of the planet's orbital period from the transit observations and the size from the change in luminosity during the eclipse. It is clear that the information content available by direct detection techniques is generally complementary to that available by indirect detection techniques.

Barnard's star is perhaps the most studied and controversial of the several stars which are astrometrically suspected to have planets or planetary systems. The astrometric data of Barnard's star taken at the Sproul observatory over the period from late 1930s to late 1960s were first analyzed by Van de Kamp (refs. 3 and 4), who claimed that the data appeared to reveal the presence of one or two low-mass dark companion(s). Several studies have since emerged, including one by Van de Kamp himself (refs. 5 and 6), concerning the accuracy and the possibilities of systematic errors in the Sproul data (refs. 7 and 8). Black (ref. 2) gives a historical summary of these controversies, concluding that there is, as yet, no good evidence for the existence of an extrasolar planet. More recent studies (D. C. Black, 1983, private communication) at the U.S. Naval Observatory do not support Van de Kamp's data on Barnard's star.

The present report concerns possible direct thermal detection of extrasolar planets using the Large Deployable Reflector (LDR), a large orbiting infrared telescope scheduled for launch by NASA in the 1990s. The scientific rationale and technological requirements for undertaking this method of detection is examined here.

To detect an extrasolar planetary system directly, a telescope must have the sensitivity to detect the planet in the presence of fluctuations in a thermal background (for LDR, this means the thermal emission from the telescope itself) as well as the spatial resolving power to resolve the planet from its central star. The sensitivity can be enhanced, for example, by lowering the emissivity of the telescope, cooling the telescope, or by increasing its area of collection. The spatial resolution is enhanced by increasing the effective diameter of the telescope, working at the shortest possible wavelengths, and by minimizing small-angle scattering.

In short, the direct detection of an extrasolar planet involves resolving an extremely dim planet which lies close to a bright star. Optimum planets will thus be bright and well separated in angle from their parent star.

Consideration of stellar-to-planet flux ratios (brightness contrast ratios) indicates (ref. 2) that the far-infrared portion of the spectrum is favored for direct detection over the visual or near-infrared portion. At short wavelengths, the radiation from the planets is mostly scattered starlight and the ratio is $\sim 10^9$ for a Sun-Jupiter combination. At the peak wavelength λ_p of the planet's thermal radiation, the ratio is $\sim 10^4$ for the same system. The optimal wavelength for

detection is presumably this peak in the planet's thermal emission, since the planet's emission falls off exponentially at shorter wavelengths.

This report is organized as follows. Section II presents an analysis of the direct detection technique using an infrared telescope which is diffraction-limited to λ_p. Scattering of infrared starlight into small angles ($\lesssim$10 arcsec) is neglected. Section III applies the results of the analysis in construction of a search strategy for the LDR by studying the nearby (<6 parsec) stars in terms of likelihood of planet detection. We consider some special circumstances that may make planet detection easier, such as a planet around a white dwarf star, or a young hot planet with large residual internal heating from gravitational contraction. Section IV summarizes and states our conclusions.

II. DETECTION WITH A DIFFRACTION-LIMITED INFRARED TELESCOPE: THEORETICAL CONSIDERATIONS

A model planetary system is shown in figure 1, where r_p and T_p denote the radius and effective surface temperature of a large (Jupiter-size) planet. The planet is a projected distance, d, away from a central star of radius, r_*, and effective surface temperature, T_*, and the star is distance, L, from an Earth-orbiting infrared telescope of diameter, D. Both the planet and the star are assumed to emit as a blackbody at these respective temperatures.

As discussed in section I, the optimum wavelength for planet detection is that of the planet's thermal emission peak, which is given by $\lambda_p = 29\ \mu m\ (100\ K/T_p)$. We make two fundamental assumptions.

1. The telescope is diffraction-limited to λ_p, so that the resolution of the planet from the central star is accomplished in the wings of the star's Airy pattern. We assume planet detection occurs when the planet-star intensity ratio exceeds unity. (The thermal emission of the planet peaks at wavelengths shorter than 30 μm for T_p > 100 K and the LDR, in practice, will probably not be diffraction-limited at these shorter wavelengths. The angular resolution will suffer. In this article, however, we assume otherwise and seek the optimum possibilities of planet detection.)

2. Scattering of starlight into small angles ($\cong$1-10 arcsec can be neglected. In other words, the scattered star intensity onto the planet pixel is less than that of the planet, which is approximately 0.01% of the intensity of the central maximum of the stellar image in the far infrared.

The calculation of planet temperature (A), sensitivity constraints on planet detection by LDR (B), and angular resolution constraints on planet detection by LDR (C) is discussed in the sections below.

A. Temperature of a Gaseous Planet

The equilibrium temperature of a planet should satisfy

$$\frac{\pi r_p^2}{4\pi d^2}(1-\alpha)\mathscr{L}_* + f_p(M_p,\tau) = 4\pi r_p^2 \sigma T_p^4 \tag{1}$$

where α is the Bond albedo of the planet, $\mathscr{L}_*$ is the stellar luminosity, and $\sigma = 5.67\times10^{-5}$ erg cm^{-2} sec^{-1} K^{-4} is the Stefan-Boltzman constant. The term on the right side of equation (1) represents the radiative loss from the planet. The first term on the left denotes the energy input from absorbed stellar radiation, and the second term is the input from the residual internal energy generated from the conversion of gravitational energy. This last term generally depends on the planet's mass, M_p, and age, τ. A semiempirical formula of the time and mass dependence of gravitationally self-generated energy for large gaseous planets ($10^{-4} \lesssim M_p/M_\odot \lesssim 10^{-3}$) is given by (ref. 1)

$$f_p(M_{pJ},\tau_9) = 9.60\times10^{-9}\ M_{pJ}^{2.35}\tau_9^{-1.22}\mathscr{L}_\odot \tag{2}$$

where τ_9 is the planet's age in units of 10^9 yr, M_{pJ} is its mass in units of the Jovian mass ($M_{Jupiter} = 0.00095\ M_\odot$), and $\mathscr{L}_\odot$ is the solar luminosity (3.83×10^{33} erg sec^{-1}). The temperature of the planet is then given by

$$T_p = 278.3\left[\frac{(1-\alpha)\mathscr{L}_{*\odot}}{d_{AU}^2} + 0.17\,\frac{M_{pJ}^{2.35}\tau_9^{-1.22}}{r_{pJ}^2}\right]^{1/4}\ \mathrm{K} \tag{3}$$

where $\mathscr{L}_{*\odot} = \mathscr{L}_*/\mathscr{L}_\odot$ is the stellar luminosity in solar units.

B. Sensitivity

Ignoring the radiation from the parent star, one constraint on the detection of a planet is that the thermal emission from the planet be sufficiently luminous to detect. Sensitivity depends both on the strength of the signal (and therefore on the planetary system parameters L, r_p, T_p) and on the amount of noise produced by the telescope system. The instrumental parameters on which the sensitivity depends, followed by projected LDR values are given:

t integration time (~10^4 sec)

η transmission efficiency of the system (~1.0)

$\Delta\nu$ frequency band pass of the detector ($\Delta\nu/\nu \sim 0.1$)

ε emissivity of the telescope (~0.05)

T_T temperature of the telescope (~200 K)

D aperture of the telescope (~20 m)

A $\pi(D/2)^2$ = area of the telescope mirror

Ω_D solid angle subtended by the telescope

The integrated number of photons received from the planet by the telescope in time, t, is given by

$$S = \frac{4\pi r_p^2 \pi (2h\nu^3/c^2)[\exp(h\nu/kT_p) - 1]^{-1} A\eta t\ \Delta\nu}{c^2 h\nu 4\pi L^2} \tag{4}$$

where h is the Planck constant and c is the speed of light. The corresponding number, N, of noise photons coming from random statistical fluctuations in the thermal emission received from the telescope is given by

$$N = \left\{\Omega_D A\varepsilon\eta t\ \frac{2h\nu^3}{c^2}\ [\exp(h\nu/kT_T) - 1]^{-1}\ \frac{\Delta\nu}{h\nu}\right\}^{1/2} \tag{5}$$

For a diffraction-limited telescope, $\Omega_D A = 3.7\lambda^2$, where λ is the wavelength of observation corresponding to frequency, ν. In order to detect the planet's signal over the fluctuations in the telescope's thermal emission, the planet must lie within a distance, L, given by

$$\frac{L}{D} \lesssim 4.49\times10^{-11}\ \frac{r_p \nu^{5/4} t^{1/4}}{(S/N)^{1/2}}\ K^{1/4}\ \frac{[\exp(h\nu/kT_T) - 1]^{1/4}}{[\exp(h\nu/kT_p) - 1]^{1/2}} \tag{6}$$

where $K = \eta\varepsilon^{-1}(\Delta\nu/\nu)$ and (S/N) is the required signal-to-noise ratio. At the wavelength of the planet's peak thermal emission, equation (6) reduces to the following equation of sensitivity:

$$\frac{L_{pc}}{D_3} \lesssim 0.906 \left[\frac{Kt_3}{(S/N)^2}\right]^{1/4} [\exp(497T_{p2}/T_T) - 1]^{1/4} r_{pJ} T_{p2}^{5/4} \tag{7}$$

where $L_{pc} = L/3.086\times10^{18}$ cm, $D_3 = D/10$ m, $t_3 = t/1000$ sec, $T_{p2} = T_p/100$ K, and $r_{pJ} = r_p/7.13\times10^9$ cm (units of Jupiter's radius). Figure 2 shows the dependence of the sensitivity on T_T (scaled to the sensitivity at $T_T = 200$ K) for various planetary temperatures. Sensitivity increases markedly for $T_T < 100$ K but, unless the planet is very warm ($T_p \sim 400$ K), cooling the telescope from 200 K to 100 K will not increase the sensitivity more than a few times.

C. Resolution

The generalization of the Rayleigh criterion for resolution in the limit of large brightness contrast between two light sources for a clear (nonapodized) aperture telescope is (ref. 2)

$$D\theta_{cr} \cong 7.11\times10^4 \lambda (F_*/F_p)^{1/3}\ \text{cm arcsec} \tag{8}$$

where (F_*/F_p) is the ratio of star-planet fluxes and θ_{cr} is the critical angular separation at which the off-axis intensity of the star equals the planet's peak emission. Since $\theta = 2.063\times10^5$ d/L arcsec in general, the resolution of the planet from its central star requires

$$\frac{L}{D} \lesssim 2.90\ \frac{d}{\lambda} \left(\frac{r_p}{r_*}\right)^{2/3} \left[\frac{\exp(h\nu/kT_*) - 1}{\exp(h\nu/kT_p) - 1}\right]^{1/3} \tag{9}$$

At the wavelength of the planet's peak emission, planets can be resolved from their parent star if they lie closer to Earth than L given by

$$L_{pc}/D_3 < 0.203(r_{pJ}/r_{*\odot})^{2/3}T_{p2}d_{AU}[\exp(497T_{p2}/T_*) - 1]^{1/3} \tag{10}$$

where L_{pc}, D_3, r_{pJ}, and T_{p2} are as defined in equation (7), and $r_{*\odot} = r_*/6.96\times10^{10}$ cm and $d_{AU} = d/1.496\times10^{13}$ cm are respectively in units of the solar radius and the mean distance between the Sun and the Earth.

Equations (7) and (10) combined with (3) then determine whether a planet of radius r_p at distance, d, from its central star, which is distance, L, from the Earth, can be detected by a diffraction-limited orbiting telescope of a clear aperture diameter of D. In what follows, these equations will be applied to specific cases of interest. As a typical set of LDR instrumental parameters, we shall take $[Kt_3/(S/N)^2]^{1/4} = 1$ and $T_T = 200$ K. The values $\Delta\nu/\nu = 0.1$, $\eta = 1.0$, $\varepsilon = 0.05$, and $t_3 = 10$ corresponds to $(S/N) = 4.47$. Also, we take $r_{pJ} = M_{pJ} = 1$ and $\alpha = 0.35$ (the value for Jupiter).

III. THE NEAREST STAR SYSTEMS

The nearest 100 stars or star components (ref. 9) have parallaxes of 0.762 arcsec (Proxima Centauri) to 0.155 arcsec (+45°2505 and +19°5116), or distances between 31 parsec to 6.45 parsec. Among those, there are 65 M-stars, 15 K-stars, six G-stars, one F-star, two A-stars, seven white dwarfs, and four unidentified types (probably faint M-stars). Rather than consider each stellar system individually in terms of detectability of their planetary companions, we choose a list of a few stellar types that are representative of the nearby stars.

A. Main Sequence Stars

Table 1 lists the parameters of the main sequence stars considered in this section. The lifetime of an A6 star is ~1.5 billion yr whereas that of the spectral-type stars later than G2 (Sun) is ~10 billion yr or longer. Thus, we choose 1 billion yr for the average age of an A6 star and 4.5 billion yr (age of the solar system) for the rest. Note that the difference in age will affect the temperature of the planet, which is some 50% higher at large separations ($d_{AU} > 10$) from an A6 star than it is for the other stars at the same location. We shall discuss the effect of planetary ages in a later subsection when we consider the possibility of detecting planetary companions to a young star.

The sensitivity and resolution constraints on L_{pc}/D_3 are shown in figure 3 as a function of the star-planet separation, d_{AU}, for selected types of main sequence stars. Two curves (dashed line for sensitivity and solid line for resolution) are associated with each star of given spectral type and age. The curved part of the sensitivity curve corresponds to increasing planet temperature as d_{AU} decreases, resulting in an increasing maximum distance, L, to which the more luminous planet can be detected if resolution constraints are ignored. The horizontal portion of the sensitivity curves corresponds to constant planet temperature as the stellar radiation becomes negligible compared with internal heating. The resolution curve also changes slope as the planet temperature changes, since the observing wavelength

changes. The sensitivity level at the age of 3 billion yr is also indicated on the figure. The region of planet detection is that which lies below the lower of the two curves for a given d_{AU}.

Notice on figure 3 that the resolution improves with decreasing stellar luminosity (M8, M0, G2) for a given age. The resolution for A6 is better than that for G2 simply because A6 is younger; therefore, the planet is warmer. If the nearby late-type main sequence stars are 3-4.5 billion yr old, as has been assumed, then a 20-m telescope can detect Jupiter-size planetary companions only out to about 4.5 parsec regardless of the star-planet separation. Improvements in sensitivity (e.g., a longer integration time and a lower telescope temperature) would extend the range of detectability. In particular, figure 3 indicates that our solar system may be a difficult one for another star system to directly detect. Jupiter (d_{AU} = 5.2) would be barely resolved from Alpha Centauri (L_{pc} = 1.3, the nearest system) using an LDR-class infrared space telescope (D_3 = 2) with the assumed instrumental parameters.

Table 2 presents a list of individual star systems in the solar neighborhood in terms of the detectability of Jupiter-size planets. The data on each system are taken from Allen (ref. 9) and Bishop (ref. 10) with the exception of the last column, which lists the minimum star-planet separation for which detection of a Jupiter-like planet is possible with a 20-m LDR. All the stars on the list are assumed to be 4.5 billion yr old unless otherwise noted in the last column.

Note that the nearest stars are not necessarily the best candidates for detection. The minimum star-planet separation depends on the spectral type of the star. Luy 789-6, which is an M7-star at 3.3 parsec, for example, is probably better than BD +36°2147, which is an M2-star at 2.5 parsec. Direct observation of Barnard's star would certainly shed new light on the controversies surrounding possible existence of dark companions.

As dynamical instabilities of planetary orbits (ref. 11) and mass transfer between stars are possible in close binaries or multiple star systems, some care must be taken in the interpretation of our results for systems such as Sirius, Procyon, and Ross 614, which all have less than 20 AU of separation between pairs. Also, in these systems, the fact that angular resolution may suffer because of overlap of stellar images should be taken into account in judging the detectability of planets around close binaries.

B. White Dwarfs

A special circumstance in which planet detection may come more easily is the case of a white dwarf with a Jupiter-size planetary companion (ref. 12). If the planet maintains a relatively warm temperature (~100 K) from its internal heat, brightness contrast in far infrared is significantly reduced (by as much as a factor of 10^3, making the star only 10 to 30 times brighter than the planet in far infrared) and the resolution is markedly improved. We note here that we are approaching the lower limit of applicability of equation (6), which was derived in the limit of large brightness contrast ratio.

Detection is now sensitivity- rather than resolution-limited. This is demonstrated in figure 4, which shows sensitivity and resolution curves for three spectral types of white dwarfs, which are listed in table 3. The sensitivity curves are almost entirely a result of the chosen ages for the planets, which determine the planet's temperature via the amount of residual gravitational heating. Also shown

in the figure are the resolution and sensitivity curves for an A2 main sequence star. A striking contrast is seen between the sensitivity-limited white dwarfs and this early-type star, which is almost entirely resolution-limited.

High sensitivity is crucial to the discovery of Jupiter-size planetary companions to white dwarf stars. With the assumed values for the instrumental parameters, a 20-m telescope can detect a Jupiter around a white dwarf within approximately 3 parsec from the Earth. The only white dwarf within this distance is Sirius B, a companion to Sirius A, which is an A1 main sequence star in the Ursa Major cluster, which is about 200 to 300 million yr old.

There are four more white dwarfs within 5 parsec of the Earth. The next nearest white dwarf, Procyon B, requires a better sensitivity than is possible with the assumed instrumental parameters, unless it is younger than the assumed age of 10 billion yr. Van Maanen's star is a white dwarf of spectral type G and, according to figure 4, our 20-m LDR telescope would need twice the sensitivity that is calculated with the assumed instrumental parameters to detect a Jupiter-size companion that is 10 billion yr old. Halving the age would also bring it within the detectable range, but it is unlikely that a single system G-type white dwarf can be much less than the assumed age. In any case, since no astrometric perturbation has been observed in association in van Maanen's star over the past 40 yr, it may be considered low on the priority list for extrasolar planetary search. Similar constraints on the instrumental sensitivity and the stellar age apply to Luy 145-141 and to Omicron (2) Eridani B, which are both A-type white dwarfs and are ~4.9 parsec away. These results are summarized in table 4.

C. Young Stars

Another special circumstance that is of great interest is the case of a young main sequence star ($\tau < 10^9$ yr) with a hot Jupiter-size planet as a companion. Present theory indicates that Jupiter was much hotter in the past than it is today due to larger residual internal heating from gravitational contraction. Equation (3) includes this effect. A hotter planet means a more luminous planet and a reduced star-planet brightness contrast, which improves the sensitivity as well as the resolution.

The results for a G2 star at various ages between 10^7 and 4.5×10^9 yr are presented in figure 5. For comparison, resolution curves for 10^7-yr-old M0, M8, and A6 stars, and a 10^8-yr-old A6 star are also shown. The horizontal lines are the sensitivity limit of L_{pc}/D_3 for a Jupiter-size planet of constant temperature from internal heating at the specified ages. The figure shows that instrumental sensitivity limits the maximum distance of planet detection, which decreases with the age of the planet from 2000 parsec at 10^7 yr ($T_p \cong 727$ K) to 2.5 parsec at 10^{10} yr ($T_p \cong 80$ K) for the assumed LDR parameters. For example, a Jupiter around a 100-million-yr-old star can be detected out to 50 parsec by a 20-m telescope at the wavelength of 8 μm if $d > 100$ AU (L/50 parsec). Assuming that the telescope is diffraction-limited at all observing wavelengths, the results indicate that the detectability of a Jupiter-size planet becomes better, the younger the planet and the later the spectral type of the parent star.

Among the young clusters in the solar neighborhood, the Ursa Major cluster and the Perseus cluster are probably the best targets for an LDR search; the former for its proximity, and the latter for its very young age. The other clusters, such as

Hyades and Pleides, are not close enough for their age to make planet detection possible within the LDR's sensitivity limit.

The age of the Ursa Major cluster has been estimated to be from 200 to 300 million yr; the Ursa Major Stream stars are approximately 270 million yr old (ref. 13). The upper limit on the distance for which the assumed LDR sensitivity allows detection of a Jupiter-size planet of this age is approximately 30 parsec. The cluster embraces our solar system and, although the "cluster distance" is 21 parsec, many of its members are closer and others are much farther away (Kappa Boo in the Ursa Major Stream, for example, is at 70 parsec). All the stars in the cluster that lie within 22 parsec of the Earth and some that are between 22 and 30 parsec distant are listed in table 5. Table 5 shows that, because of their young age, some of the stars in this cluster are equally good candidates for planet detection as the nearest stars in the immediate solar neighborhood listed in table 2, assuming diffraction-limited performance of LDR at $\lambda \approx 10$ μm.

The Perseus cluster, although 167 parsec away, is so young (age = $1\text{-}5\times10^7$ yr) that it is well within the upper limit on the distance placed by the sensitivity for planet detection of more than 200 parsec. Assuming that the gas and dust remnants surrounding newly formed stars have been mostly dispersed or accreted away, many late-type stars (e.g., M stars) in this cluster may have young Jupiter-like planets which are hot enough (~700 K) to be observed by our LDR if they lie $\gtrsim$30 AU from their central star (see fig. 5). Note, however, that detection assumes diffraction-limited performance of LDR at the peak in the planet's thermal emission, which lies at $\lambda \cong 4\text{-}5$ μm. Such performance is a severe technological constraint on LDR capabilities and is unlikely to be achieved.

CONCLUSIONS

Direct detection of the thermal emission from extrasolar planets has been investigated as one of the possible uses of the LDR. A promising aspect of the LDR is its far-infrared wavelengths of operation because the best wavelength for observation of an extrasolar planet is presumably in the typically far-infrared peak in the planet's thermal emission. The star-planet brightness contrast is $\lesssim 10^4$ in the far-infrared as compared to $\sim 10^9$ in the visible portion of the spectrum for a Sun-Jupiter system.

A telescope must have the sensitivity to detect planetary signals over noise fluctuations and the spatial resolving power to detect an extremely dim planet which lies close to a bright star. Consideration has been given to these two major observational constraints in the calculation of the detectability of Jupiter-size planetary companions to main sequence stars, white dwarfs, and young stars. It is assumed that (1) the LDR is diffraction-limited to the operating wavelength so that the resolution of the planet from the central star is accomplished in the wings of the star's Airy pattern, and that (2) the scattered starlight onto the planet pixel is negligible.

The results are presented in terms of the constraints on the distance-to-aperture ratio as a function of the angular separation of the star-planet system. Proxima Centauri, Barnard's Star, Wolf 359, and Epsilon Eridani are just a few of the many nearest main sequence stars that can be probed in a search for Jupiter-size planets by the LDR. We find that, because of internal heating, the detectability of a Jupiter-like planet improves markedly with a reduction of the star-planet brightness contrast (young, low-luminosity stars with hot planets or planets around very low-luminosity M-type stars and white dwarfs). If white dwarfs are as old as they are

usually assumed to be (5-10 billion yr) then only the nearest white dwarf (Sirius B) is within the detectable sensitivity range of LDR. The other four white dwarfs within 5 parsec need better sensitivity in LDR instrumentation. The younger (thus hotter) the planet is, and the later the spectral type of the parent star is, the easier it is to detect a Jupiter-size planet. Because of their proximity and young age, the Ursa Major cluster and the Perseus cluster are within the LDR's detection range. Other candidates might include the nearby infrared astronomy satellite (IRAS) objects with extended far-infrared emission from, presumably, protoplanetary disks and T Tauri stars in the Taurus molecular cloud.

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TABLE 1.- MAIN SEQUENCE STARS

$M_*/M_\odot$	Sp	$\mathscr{L}_*/\mathscr{L}_\odot$	$r_*/r_\odot$	T_* (K)	τ_9
3.0	A2	70.80	2.40	10744	0.3
2.0	A6	15.85	1.60	9040	1.0
1.0	G2	1.00	1.00	5770	4.5
.5	M0	.071	.60	3812	4.5
.1	M8	.0013	.126	3063	4.5

TABLE 2.- THE NEAREST STAR SYSTEMS

Name	1980 R.A., hr min	1980 Dec, deg min	L_{pc}, parsec	Sp	Notes	Minimum d_{AU} detectable, AU
Alpha Cen A	14 38	-60 46	1.32	G2v	AB = 23 AU	4.2
B				K4v	BC = 10^4 AU	3.5
Proxima Cen C	14 28	-62 36		M5		1.6
Barnard's	17 56	+04 36	1.81	M5v	iv cp	3
Wolf 359	10 56	+07 10	2.32	M8	fl	2
BD+36°2147	11 03	+36 07	2.49	M2v	iv cp	5
Sirius A	6 44	-16 42	2.65	A1v	See table 5	
B				DA	See table 4	
Luy 726-8 A	1 37	-18 04	2.74	M5	AB = 11 AU	4
B				M5		4
Ross 154	18 49	-23 50	2.90	M5	fl	4.5
Ross 248	23 40	+44 04	3.15	M6		4
Epsilon Eri	3 32	-09 32	3.28	K2v	iv cp?	10
Luy 789-6	22 38	-15 28	3.31	M7		3
Ross 128	11 47	+00 58	3.32	M5		5
61 Cygni A	21 06	+38 38	3.42	K5v	AB = 85 AU	11
B				K7v	B iv cp	12
Epsilon Indi	22 03	-56 52	3.44	K8v		12
Procyon A	7 39	+05 17	3.48	F5v	AB = 16 AU	16
B				DF	See table 4	
Sigma 2398 A	18 42	+59 36	3.52	M4	AB = 60 AU	6
B				M5		6
BD+43°44 A	0 18	+43 54	3.55	M1v	A sp db, B fl	10
B				M6v	AB = 156 AU	5
CD-36°15693	23 05	-35 59	3.58	M2v		8
Tau Ceti	1 43	-16 03	3.66	G8vi	Subdwarf	13
G51-15	8 29	+26 51	3.66	?	Probably M8	3
BD+5°1668	7 27	+05 27	3.76	M5	db? iv cp?	6
Luy 725-32	1 11	-17 06	3.82	M5		6
CD-39°14192	21 16	-38 58	3.85	M0v		11
Kapteyn's	5 11	-44 59	3.91	M0		11
Kruger 60 A	22 27	+57 36	3.94	M3	AB = 9.5 AU iv cp	8
B				M4.5		7
Ross 614 A	6 28	-02 48	4.02	M7	AB = 4 AU	4
B				?		
BD-12°4523	16 30	-12 36	4.02	M5	sp db	6
van Maanen's	0 48	+05 19	4.27	DG	See table 4	
Wolf 424 A	12 33	+09 09	4.37	M6	AB = 3 AU	6 (3 bil)
B				M6		6 (3 bil)
G158-27	0 06	-07 38	4.42	?	Probably M8	4 (3 bil)
CD-37°15492	0 04	-37 27	4.44	M4		8 (3 bil)
BD-50°1725	10 10	+49 33	4.61	K7v		20 (3 bil)
CD-46°11540	17 28	-46 53	4.63	M4		8 (3 bil)
CD-49° 13515	21 32	-49 11	4.67	M1v		12 (3 bil)
CD-44°11909	17 37	-44 17	4.69	M5	iv cp	8 (3 bil)
G208-44	19 53	+44 21	4.69	?	Probably M8	5 (3 bil)
Luy 1159-16	1 59	+13 00	4.72	M8v	fl	5 (3 bil)

Sp: v = main sequence, dwarf; vi = subdwarf.
Notes: iv cp = invisible companion; sp = spectroscopic; db = double; fl = flare.
Minimum d_{AU}: A Jupiter-size planet would need to lie at least this distance from the star to be detected by LDR. Beyond Luy 1159-16, only very young (hot) planets can be detected by LDR. Assumed age of planets is 5 billion yr unless noted in parentheses (bil = billion yr).

TABLE 3.- WHITE DWARFS

Sp	$\mathscr{L}_*/\mathscr{L}_\odot$	$r_*/r_\odot$	T_* (K)	τ_9
DA	2.5×10	0.013	11500	7
DF	1.7×10	.01	6600	10
DG	3.7×10	.01	4500	10

TABLE 4.- WHITE DWARFS WITHIN 5 PARSEC

Name	1980 R.A., hr min	1980 Dec, deg min	L_{pc}, parsec	Sp	Notes and detectability
Sirius B	6 44	-16 42	2.65	DA	AB = 19 AU, $d_{AU} > 1$
Procyon B	7 39	+05 17	3.48	DF	AB = 16 AU, $d_{AU} > 1$ if age < 7 bil yr
van Maanen's	0 48	+05 19	4.27	DG	Needs 2X sensitivity or age < 5 bil yr
Luy 145-141	11 44	-64 42	4.85	DA	Needs 2X sensitivity or age < 4 bil yr
Omic(2) Eri B	4 14	-07 41	4.88	DA	AB = 400 AU, BC = 34 AU, needs 2X sensitivity or age < 4 bil yr

TABLE 5.- THE NEAREST STARS IN THE URSA MAJOR CLUSTER (AGE = 2.7 MILLION YR)

Name	1950 R.A., hr min	1950 Dec, deg min	L_{pc}, parsec	Sp	Notes	Minimum d_{AU} detectable, AU
Sirius A	6 43	-16 39	2.65	A1v	AB = 19 AU	10
B				DA		1
Xi Boo A	14 49	+19 18	6.76	G8v	UMa stream, AB = 33 AU	8
B				K4v		7
Gamma Lep A	5 42	-22 28	8.13	F6v	AB = 764 AU	13
B	5 42	-22 26		K2v		9
Chi(1) Ori	5 51	+20 16	9.90	G0v		16
36 UMa A	10 27	+56 14	12.05	F8v	DM+56°1459, AB = 1446 AU	18
B	10 27	+56 15		K7v	DM+56°1458	13
Gamma Cet A	2 41	+03 16	12.66	A2v	AB = 35 AU	50
B				F3	Dwarf	20
C	2 40	+03 10		K5	DM+2°418	13
10 UMa A	8 57	+41 59	13.51	F5v	DM+42°1956	25
B				?	AB = 8.5 AU	
47 UMa	10 57	+40 42	13.51	G0v	DM+41°2147	22
9 Pup A	7 49	-13 46	14.49	G1v	DM-13°2267, UMa stream?	23
B				?	AB = 8.4 AU	
Iota UMa A	8 56	+48 14	15.15	A7v	9 UMa	40
B				M1	AB = 162 AU	15
C				?	BC = 10 AU	
Alpha Crv	12 6	-24 27	15.15	F2v	Sirius group?	30
Pi(1) UMa	8 35	+65 12	15.63	G0v	3 UMa, Sirius group	25
Eta Crb A	15 21	+30 28	16.67	G2v	AB = 15 AU	25
B				G2v		25
Alpha Oph	17 33	+12 36	16.67	A5iii	UMa stream, iv cp = 1 AU	44?
Delta Leo	11 11	+20 48	16.95	A4v	Sirius group	50
Delta Vel A	8 43	-54 32	20.00	A0v	UMa group? quadruple	120
B					AB = 52 AU	
C		-54 31			AC = 1384 AU	
D					CD = 124 AU	
Tau(3) Eri	3 0	-23 49	21.28	A4v	UMa stream	70
16 UMa	9 10	+61 38	21.74	F9	DM+62°1058, dwarf	35
24 UMa	9 30	+70 03	21.74	G4iv?	DM+70°565	30
Delta UMa	12 13	+57 19	22.73	A3v	UMa nucleus	90
Iota Leo A	11 21	+10 48	23.81	F2iv	UMa stream? AB = 48 AU	40
B						
Rho Cap A	20 26	-17 59	25.64	F2iv	Sirius group, AB = 103 AU	42
B						
Vys 688	13 21	+58 10	25.64	M0v	UMa nucleus	25
DM+57°1425	13 12	+56 58	27.03	G1.5v	UMa nucleus	47

Sp: iii = giant; iv = subgiant; v = main sequence, dwarf.
Notes: UMa = Ursa Major; iv cp = invisible companion.
Minimum d_{AU}: Minimum separation of Jupiter-star combination for LDR detection, assuming diffraction-limited performance of LDR at the peak in the planet's thermal emission ($\lambda \approx 6$ μm).

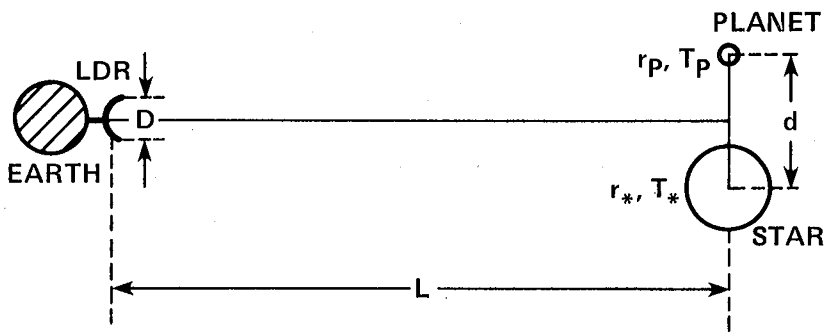

Figure 1.- The parameters of a planetary system.

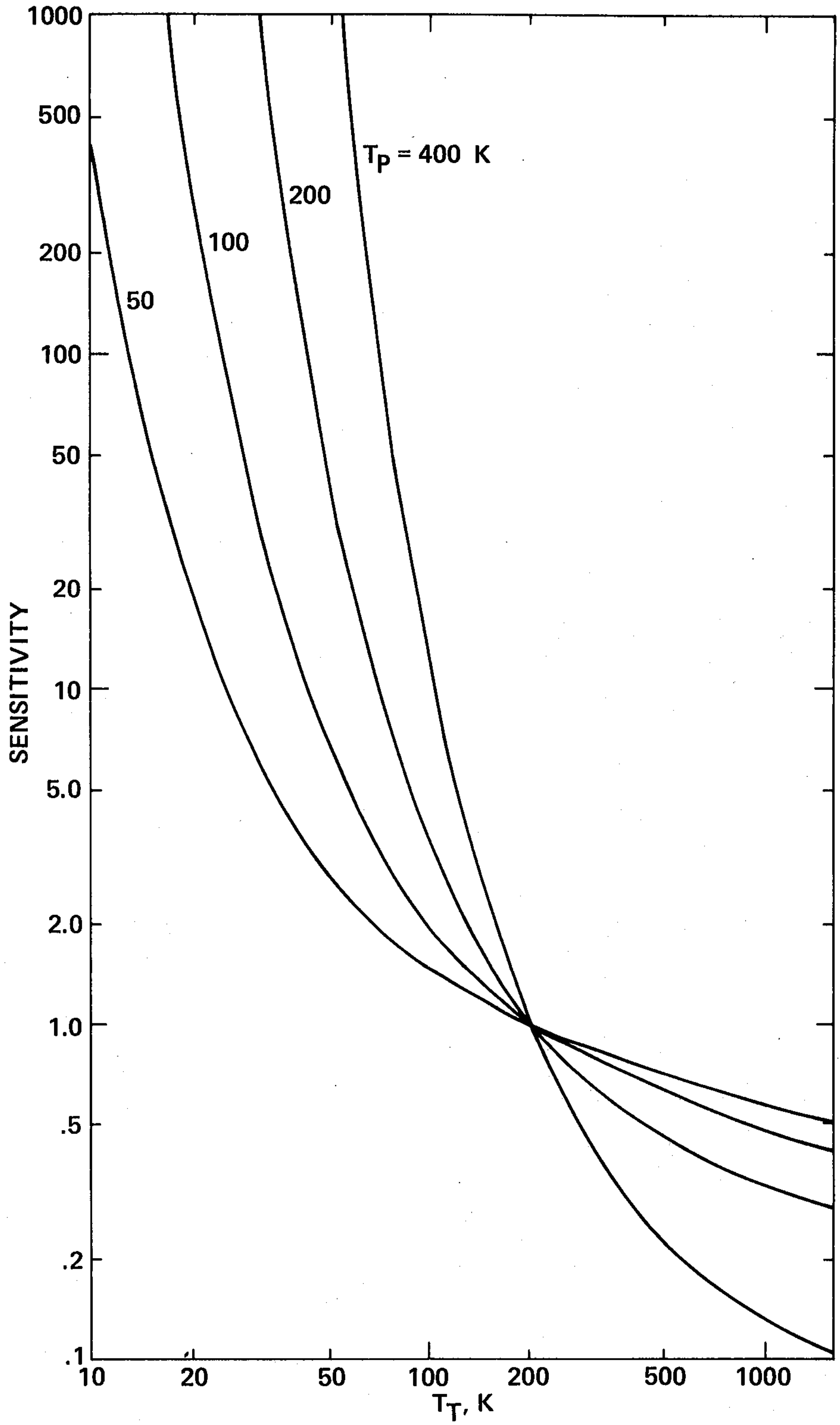

Figure 2.- The dependence of the instrumental sensitivity on the telescope temperature. Sensitivity = 1 for T_T = 200 K.

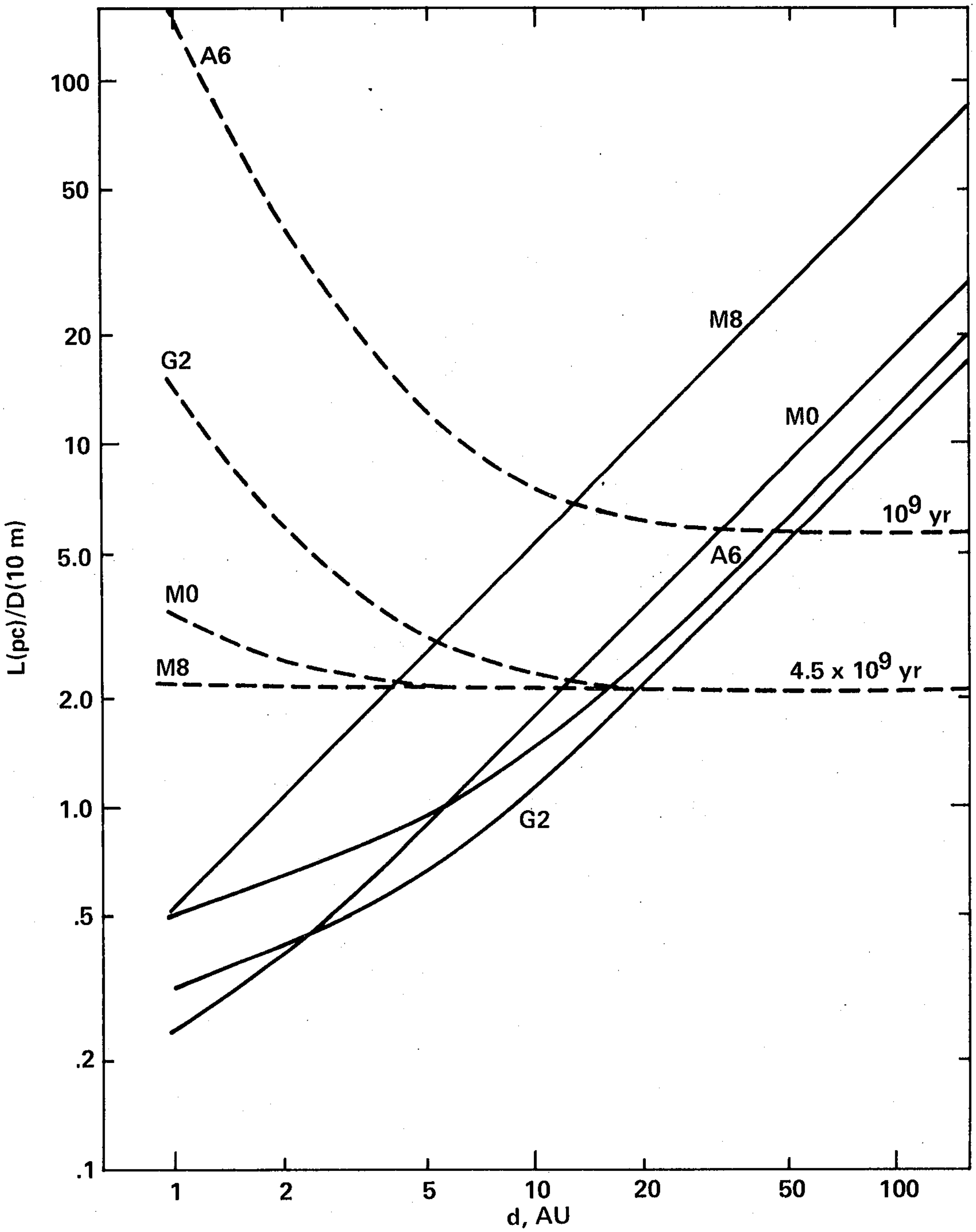

Figure 3.- The upper limit on the distance L_{pc} (in units of parsec) to which a single aperture of diameter D_3 (in units of 10 m) in orbit can resolve (solid lines) or have sufficient sensitivity (dashed lines) to detect a Jupiter-size planetary companion to a select number of main-sequence stars, shown as functions of star-planet separation d_{AU} (in units of AU). Planet detection is possible below both the sensitivity and resolution curves. The stars are assumed to be 4.5 billion yr old except for the A6 star, which is assumed 1 billion yr old.

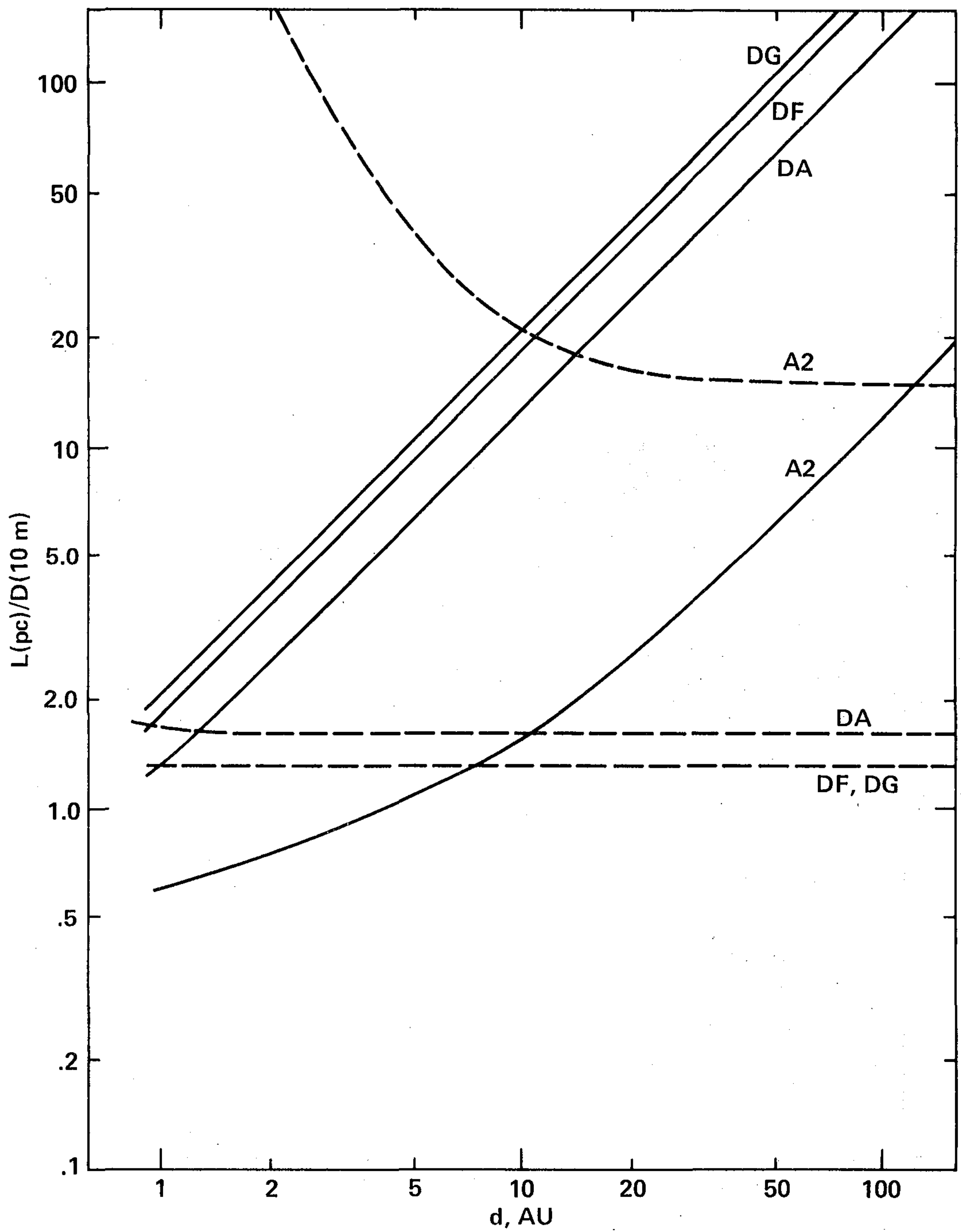

Figure 4.- Same as figure 3, but for white dwarfs. The age of the DA white dwarf is assumed to be 7 billion yr and that of the DF and DG to be 10 billion yr. Curves for a 200 million yr old A2 main sequence star are also shown.

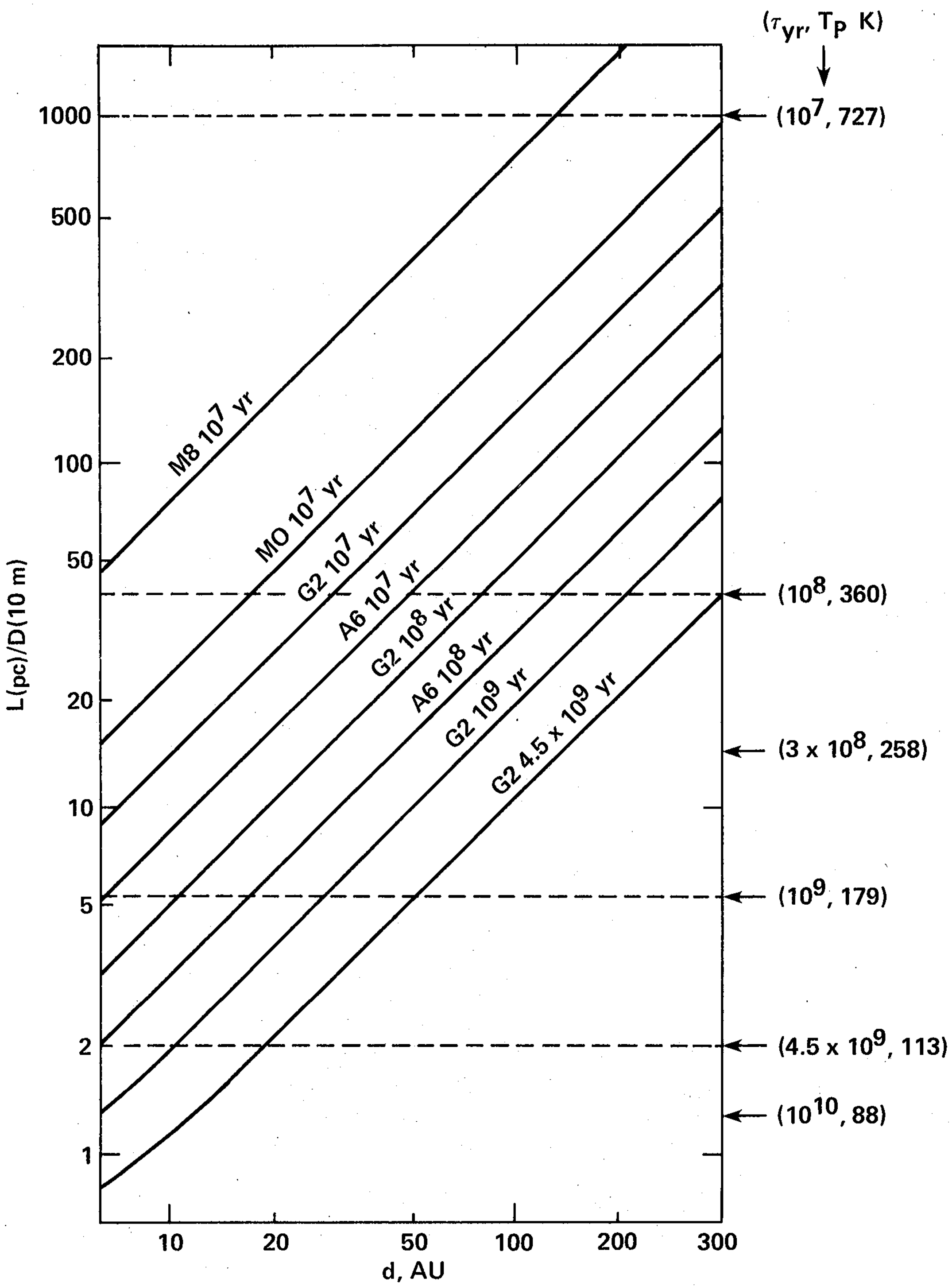

Figure 5.- Same as figure 3, but for a G2 star of different ages. The sensitivity curves are determined by the planet's temperatures at different ages. Also shown are the resolution curves for an A6 star of ages 10 and 100 million yr and MO and M8 stars of age 10 million yr.

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16. Abstract

Direct detection of the thermal emission from extrasolar planets has been investigated as one of the possible uses of the Large Deployable Reflector (LDR), an orbiting infrared telescope scheduled for launch by NASA in the 1990s. Consideration has been given to two major observational constraints, namely, instrumental sensitivity and angular resolution, in the calculation of detectability of Jupiter-size planetary companions to main sequence stars, white dwarfs, and young stars.

The best wavelength for observation of planetary companions to stars other than the Sun is one at which a planet's thermal emission is strongest; typically this would occur in the far-infrared region, because in this area of the spectrum, the star-planet brightness ratio is much less than it is in the visible portion of the spectrum for a wide range of possible star-planet combinations. It is assumed that the telescope is diffraction-limited so that the resolution of the planet from the central star is accomplished in the wings of the star's Airy pattern. Proxima Centauri, Barnard's Star, Wolf 359, and Epsilon Eridani are just a few of the many nearest main-sequence stars that could be studied with the LDR.

The detectability of a planet improves for warmer planets and less luminous stars; therefore, we have considered the cases of planets around white dwarfs and those young planets which have sufficient internal gravitational energy release so as to cause a significant increase in their temperatures. If white dwarfs are as old as they are usually assumed to be (5-10 billion yr), then only the nearest white dwarf (Sirius B) is within the range of LDR. The Ursa Major cluster and Perseus cluster are within LDR's detection range mainly because of their proximity and young age, respectively.

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